

Quantum Materials Studies at the *In-Situ* and Resonant Scattering Beamline, 4-ID

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Scientific Programs and Beamline Specs

– Science focus areas:

- **Physics of quantum materials**
- Atomic structure of functional surfaces and interfaces
- Time-resolved studies of growth and materials processes

– Key capabilities:

- Tender and hard x-rays (2.4-23 keV)
- Variable focusing down to $\sim 20 \mu\text{m}$ (H) x $2 \mu\text{m}$ (V)
- Polarization control
- Custom endstations, including gas handling system infrastructure

Parameter	Specification/Description
Insertion device:	IVU23, 2.8-m long, in a high- β straight
Operating energy range:	2.4 – 23 keV
Monochromator:	Fixed-exit Si(111)
Beam size at sample (FWHM):	Tunable down to 20 (H) x 2 (V) μm^2
Flux at sample (500 mA ring current):	$\sim 10^{13}$ photons/s
Harmonic suppression:	$\sim 10^{-5}$ for third harmonic with fundamental at 3 keV
Polarization control:	$P_{L,C} \geq 0.9$ for $2.4 \text{ keV} \leq E \leq 14 \text{ keV}$
Custom endstations:	3 endstations: base diffractometer for high magnetic field studies, instrumented 6-circle diffractometer, and base diffractometer for <i>in-situ</i> studies of growth and materials processes with gas handling system infrastructure

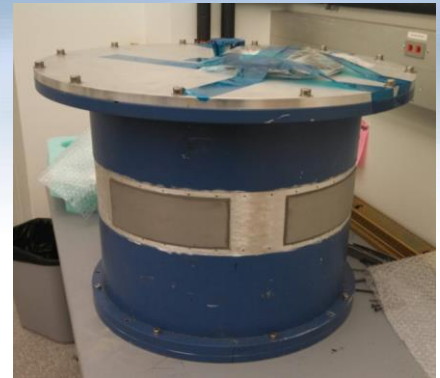
Endstation Hutch 4-ID-C

Instrumented 6-Circle Diffractometer



- Horizontal and vertical plane scattering with large accessible Q range
- Dual 2θ arms for simultaneous mounting of point and area detectors
- In-vacuum polarization analyzer
- Motorized cryostat carrier

High-Field Magnet Endstation (to be commissioned in FY19)

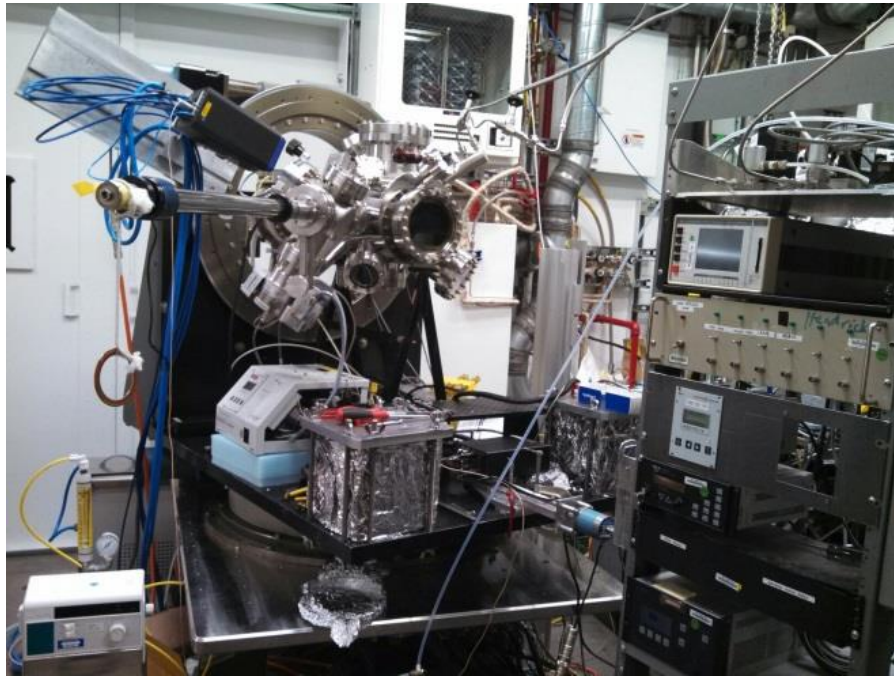


- Horizontal plane scattering
- Polarization analyzer
- Scattering magnet specifications:
 - Vertical field: up to ~ 10 T
 - Sample temperature: 1.8-300 K

Endstation Hutch 4-ID-D

Program contact:
Kenneth Evans-Lutterodt

In-Situ Diffractometer and Partner User-Supplied Growth Chamber



- Secondary focusing using KB mirrors
- Gas handling system
- Excimer laser
- Pixel array detector:
 - Millisecond time resolution
 - High Q resolution



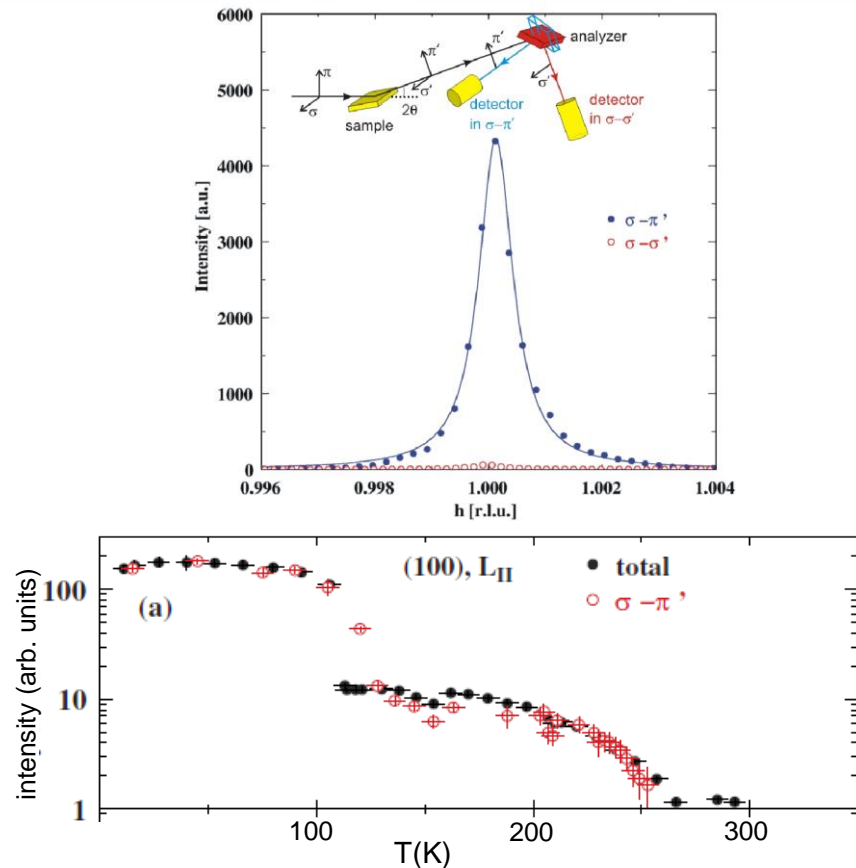
Gas Cabinets



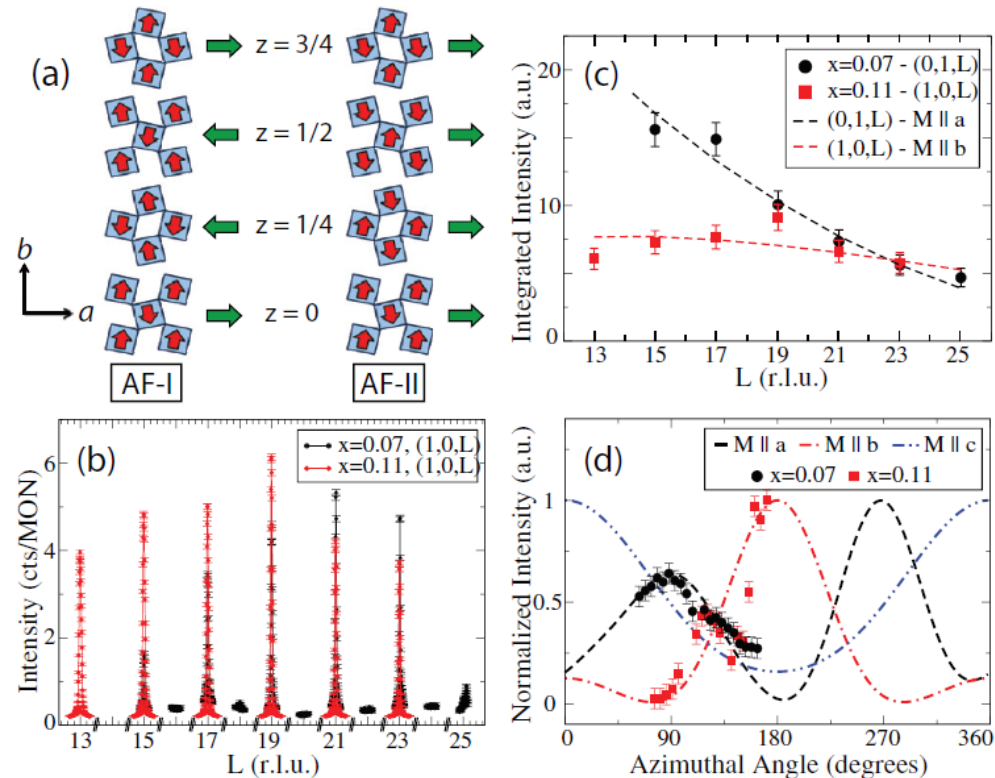
Excimer Laser



Resonant X-ray Scattering from 4d- and 5d-based Oxides

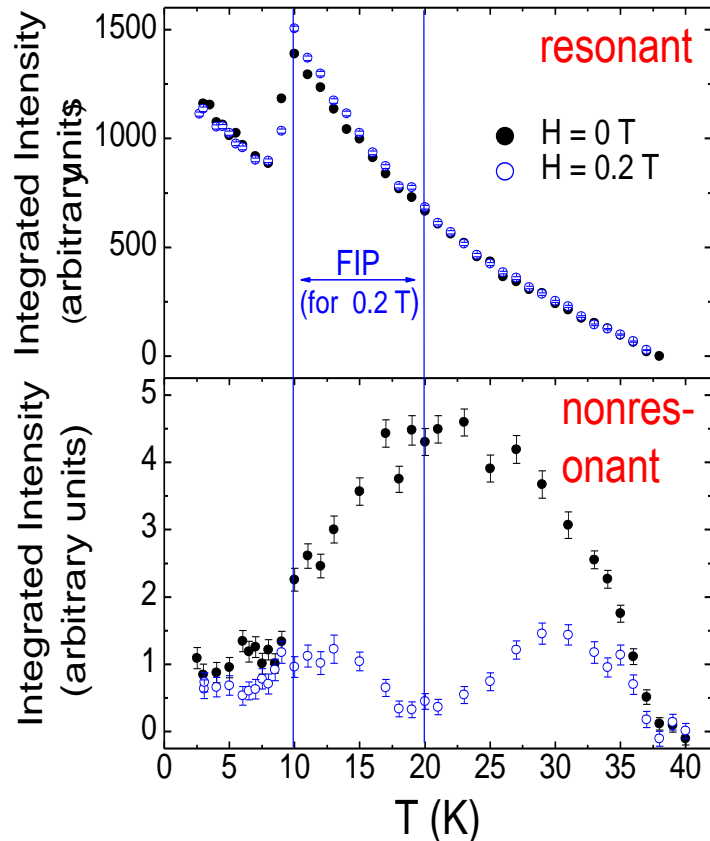


Orbital ordering transition observed in **Ca₂RuO₄**. Zegkinoglou *et al.*, PRL **95**, 136401 (2005).

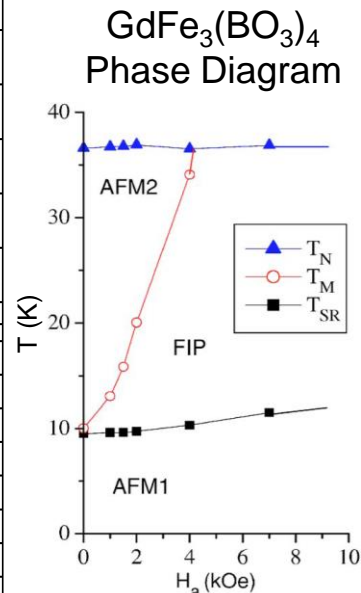


Characterization of doping-induced change in the magnetic order of **Sr₂Ir_{1-x}Rh_xO₄**. Clancy *et al.*, PRB **89**, 054409 (2014).

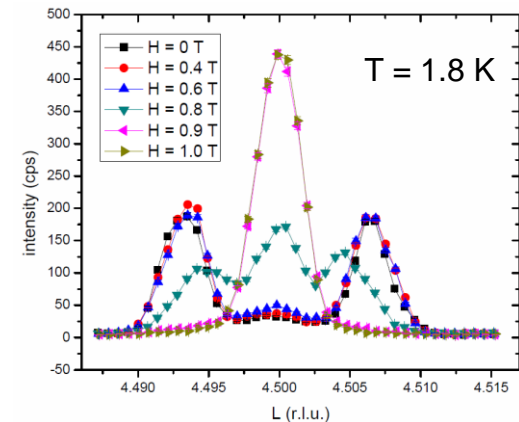
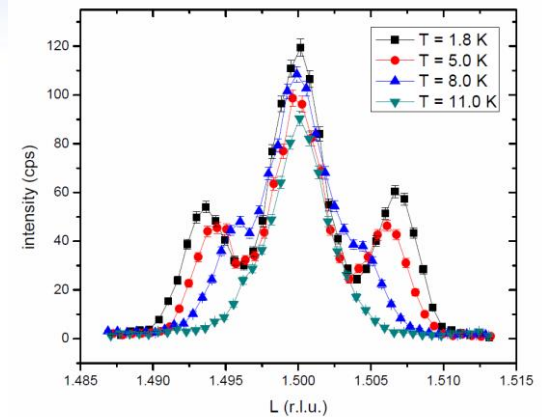
Magnetic Order in Multiferroic Rare Earth Ferroborates



Magnetic structure of $\text{GdFe}_3(\text{BO}_3)_4$ solved using magnetic x-ray scattering. Mo *et al.*, PRB **78**, 214407 (2008).



from Yen *et al.*, PRB **73**, 054435 (2006)

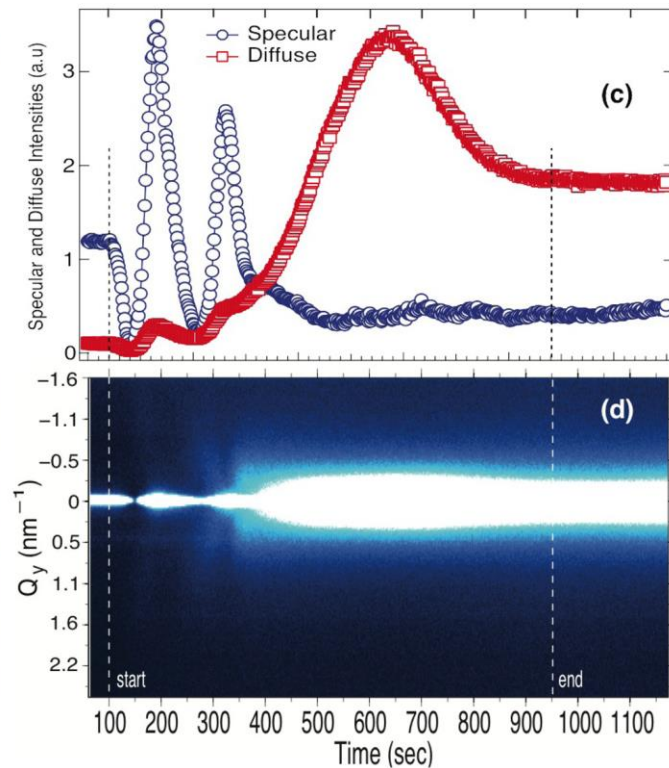
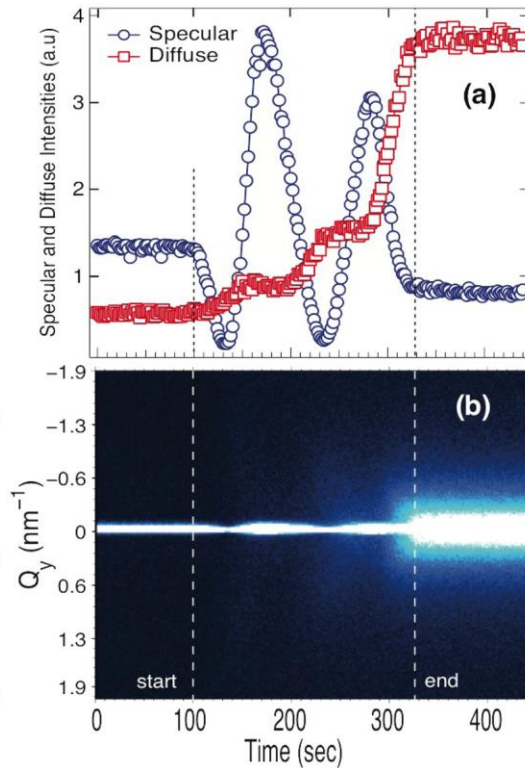
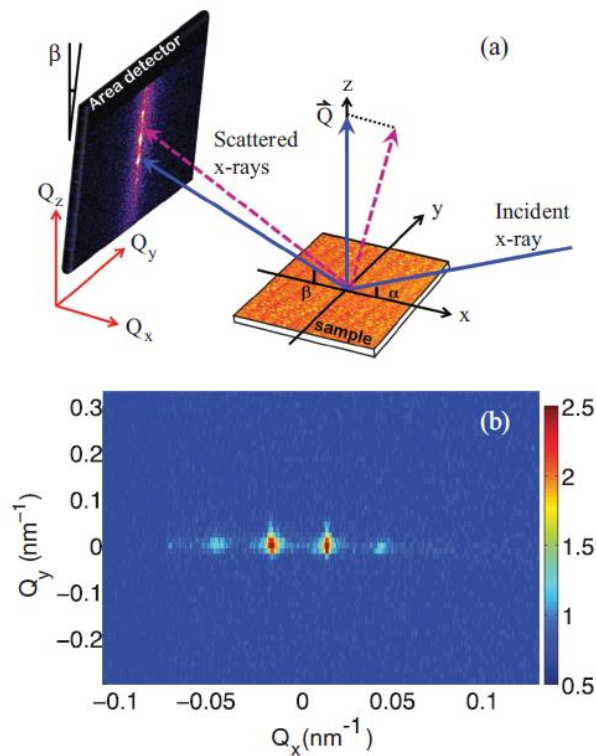


Temperature- and magnetic field-tuning of magnetic phases in $\text{NdFe}_3(\text{BO}_3)_4$. Nelson *et al.*, JKPS **62**, 1410 (2013).

In-Situ Studies of BiFeO₃ Thin Film Growth

5 Hz Laser Repetition Rate

2 Hz Laser Repetition Rate



Laminar-to-3D growth mode transition at ~ 2.5 unit cells in pulsed laser deposited BiFeO₃. Chinta *et al.*, APL **101**, 201602 (2012).

Current and Near-Future Beamline Capabilities

- Single-crystal resonant x-ray scattering with hard (6-23 keV) x-rays, ~100 μm beam
- *In-situ* studies of materials growth at surfaces and interfaces with hard x-rays (8-23 keV), with optional use of gas flow control and handling capabilities for non-hazardous gases, ~100 μm beam
- Secondary focusing down to ~20 μm (H) x 2 μm (V) with *in-situ* endstation (available in early 2018)
- Polarization control with hard (6-14 keV) x-rays (available in early 2018)
- Tender (2.4-6 keV) x-ray scattering with harmonic rejection and polarization control (available in late 2018)
- Growth processes using hazardous gases (available in 2019)
- Scattering in high magnetic field (available in 2019)

Accessible Edges in ISR Energy Range (2.4-23 keV)

1 H Hydrogen 1.00794																	2 He Helium 4.00260													
3 Li Lithium 6.941	4 Be Beryllium 9.012182																													
5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00644	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797																									
11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050	13 Al Aluminum 26.9815384	14 Si Silicon 28.0855	15 P Phosphorus 30.9737615	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948																							
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938040	26 Fe Iron 55.9349	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.921595	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80													
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 101.0730	46 Pd Palladium 106.92	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29													
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 La Lanthanum 138.9055	58 Ce Cerium 140.12	59 Pr Praseodymium 140.90768	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.9348	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.967														
73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.980399	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)	87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	90 Th Thorium (232)	91 Pa Protactinium (231)	92 U Uranium (238)	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Planned Additional Capabilities

- Sub-100 μm horizontal focusing for 6-circle diffractometer
- Coherent scattering:
 - Dynamics of charge, orbital, and magnetic domains
 - Domain imaging
- XMCD (requires horizontal magnetic field)
- Diamond anvil cell in high-field magnet